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De-spinning of a metal cylinder by induced eddy currents-application to satellite de-spinning

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Abstract : Using an external d.c. magnetic field, the effect of induced eddy currents on a spinning metallic cylinder with a view to reduce its rotational energy has been investigated. Two concepts have been analyzed : (i) a current loop positioned symmetrically around the cylinder and (ii) magnet system positioned close to the cylinder. Closed form solutions for the interacting magnetic flux are given along with details of magnetic design and current loop. A possible application is in the de-spinning of disabled satellites before servicing.

Keywords : Satellite de-spinning, induced eddy currents, interacting magnetic flux, closed-form solutions.

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1. Introduction

The servicing disabled satellites requires that the units be de-spun before any repair can be done. One way to accomplish this is by physical attachment of equipment or astronauts with equipment that would take the rotational energy out of the satellite. As an alternative, a system without physical contact with the satellite that would reduce the spin to a very low value within a reasonable time is a possibility. One such scheme is to induce eddy-currents in the metal exterior of the satellite by electromagnetic means. This eddy current power input would act in such a way as to reduce the rotational energy of the satellite.

In this paper, two methods for inducing eddy-currents have been investigated : (i) a large diameter current loop positioned around the metal cylinder (satellite), such that the axis of the cylinder is in the plane of the loop and (ii) a magnet either a bar or U-shaped positioned close to or surrounding the metal cylinder. Closed-form solutions for the interacting magnetic flux are given for the two cases. Parameters for the magnet designs are discussed along with the power requirements and estimates of the weight of the two systems.

2. Theoretical analysis

Expression for the interacting magnetic flux density :

(i) Current-loop source :

Assuming the configuration shown in Figure 1, the magnetic flux density components in cylindrical coordinates are (Kadaba 1983) :

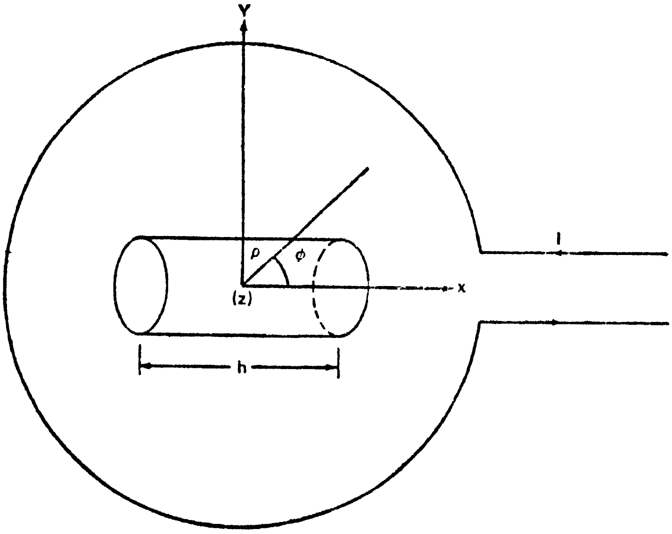

Figure 1. Configuration of the satellite positioned symmetrically with respect to the current loop ; rotation axis of the cylinder is in the plane of the current loop.

$$B_\rho = \frac{\mu_0 NI}{2\pi} \frac{z}{\rho[(a+\rho)^2+z^2]^{1/2}} \left[-K + \frac{(a^2+\rho^2+z^2)}{[(a-\rho)^2+z^2]} E \right]$$

$$B_z = \frac{\mu_0 NI}{2\pi} \frac{1}{[(a+\rho)^2+z^2]^{1/2}} \left[K + \frac{(a^2-\rho^2-z^2)}{[(a-\rho)^2+z^2]} E \right]$$

$$B_\phi = 0 \tag{1}$$

where NI is the ampere-turns, a, is the radius of the current loop, K and E are, respectively, complete elliptic integrals of the first and second kind and ρ, ϕ and z are coordinate variables in cylindrical coordinate system.

The flux linkage $d\psi$ when an element of length dx, in the skin of the cylinder rotates through an angle $d\alpha$ is given by :

$$d\psi = (\bar{B}.\bar{\mathrm{I}}) d_s dx d\alpha \tag{2}$$

where the unit vector $\bar{\mathrm{I}} = (\cos \alpha)\bar{a}_y + (\sin \alpha)\bar{a}_z$ and d_s is the radial distance to dx from the rotational axis of the cylinder. Substituting for the unit vector $\bar{\mathrm{I}}$ in eq. (2) and using $a = d_s \sin \alpha$ and

$d\alpha = \frac{dz}{\sqrt{(d_s^2 - z^2)}}$ eq. (2) becomes :

$$d\psi \quad B_y dxdz \quad \frac{B_z zdxdz}{\sqrt{(d_s^2 - z^2)}} \tag{3}$$

where B_y and B_z are the Cartesian flux components. The motional emf E, generated is given by :

$$E \quad 2\left[\int_{z=0}^{z=d_s \sin\alpha_1} \int_{x=0}^{h/2} \left\{B_y + \frac{zB_z}{\sqrt{(d_s^2 - z^2)}}\right\} dxdz\right] \tag{4}$$

where $\alpha_1 \quad \frac{2\pi(\mathrm{rpm})}{60}$. The eddy current power input P_s to the cylinder is then given by :

$$P_s - \int_{r=d_{s1}}^{r=(d_{s1}+T/2)} \frac{E^2 \pi r dr}{2\rho h} \tag{5}$$

where d_{s1} is the radial distance to the inner surface of the cylinder and T is the thickness of the wall of the cylinder, h is the length of the cylinder and ρ is the resistivity of the cylinder wall material.

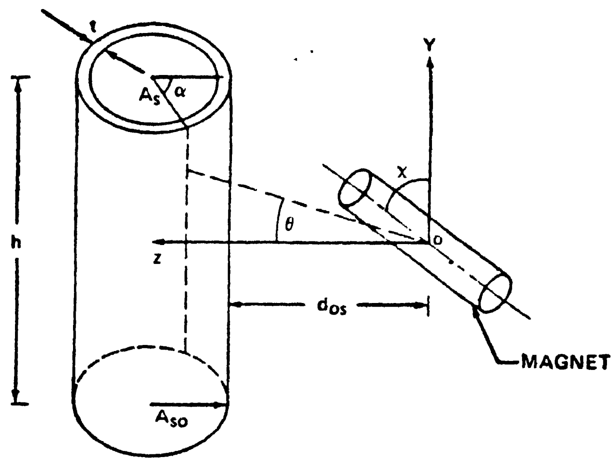

Figure 2. Configuration for the magnet system : origin of coordinates is at the center of the magnet with the axes as shown. Length of the magnet = D meters ; radices of the magnet = A meters.

(ii) Magnet source :

Using the configuration shown in Figure 2, the flux linkage in time (dt) by the spinning cylinder is given by (Smyth 1989) :

$$\bar{B}.d\bar{S} = B_x dS_x + B_s dS_s \tag{6}$$

where

$$dS_s = -(dxdy) \text{ and } dS_x = \frac{xdxdy}{\sqrt{(A_s^2 - x^2)}}$$

Here A_s is the radial distance from the axis of the cylinder to a general point in the cylinder-wall. The motional emf E, generated is then :

$$E = 2l \int_{y=0}^{y=\frac{h}{2}} \int_{x=0}^{x=A_s \sin \alpha_1} \left\{ \frac{xB_x}{\sqrt{(A_s^2 - x^2)}} - B_s \right\} dxdy \tag{7}$$

where, $\alpha_1 = \frac{2\pi(\text{rpm})}{60}$. The eddy current power input P_s is given by :

$$P_s = \int^{r=(d_{s1}+\frac{T}{2})} \frac{E^2 \pi r dr}{2\rho h} \tag{8}$$

where the parameters in eq. (8) have the same meaning as in eq. (5).

The use of a V-shaped electromagnet as shown in Figure 3 would provide for more efficient coupling between the interacting flux and the spinning cylinder than

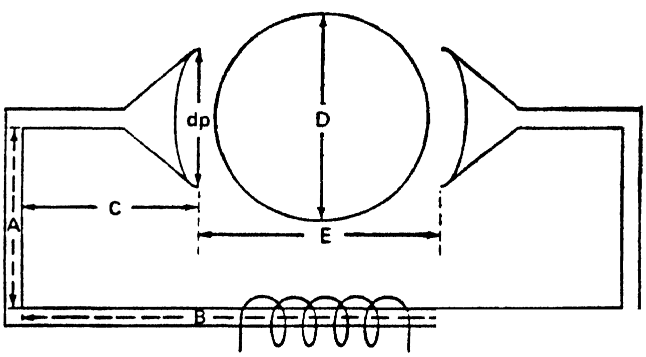

Figure 3. Sketch of the electromagnet with flared pole faces ; typical dimensions in meters : $A = 1.55$; $B = 4.5$, $C = 0.25$; $D = 3$; $E = 4$; $dp = 1.5$.

for the case of the linear magnet source discussed above. Further details will be outlined in Section 3.

3. Design considerations

A possible application of the above analysis is in the de-spinning of defunct satellites in outer space which would make the recovery of these satellites less hazardous. In this type of application, the weight and power input to the source would be a major consideration. These considerations are dealt with briefly for the two sources.

(i) Current-loop source :

The design considerations outlined below are for 9000 ampere-turns through the current loop which should lead to despin times within the orbital daylight. At room temperature for 3 mm diameter wire that can carry 45 amps, the number of turns of the loop required is 200. For a 10-meter diameter coil, this requires a length of wire of about 4400 meters. If aluminum is used as the material for the wire, the resistance of the coil would be about 14 ohms. This should make the I^2R power input to the coil rather high—about 29 K.W. At liquid nitrogen temperature, the resistivity of aluminium is estimated to be 10^{-9} ohm-meter using data at 100° K and 50° K (Nussbaum 1965). With a current of 45 amperes, this leads to a total coil resistance of 0.53 ohms. The voltage drop across the coil is then 23.8 V and the I^2R power input is 1.073 K.W. Using 1 mm diameter wire for the 200 turn coil at liquid nitrogen temperature, the total cross-sectional diameter of the coil conductor without the cooling jacket would be 1.4 cm. With cooling jacket and insulation, the overall diameter of the insulated coil conductor would be about 7.5 cms or 3 inches, an acceptable dimension. The overall weight of the current loop would be about 200 lbs.

One could envision using superconductor material for the current loop for example. Niobium-germanium tape operated at slush hydrogen temperature—around 17 or 18° K. For this purpose, Nd-Ge 10μ thick is deposited on copper substrate by (CVD) and plated with hastelloy to provide strength. The overall thickness of the tape is 15 mils and $\frac{1}{4}$ inch wide (Braginski and Katz 1977).

(ii) U-Shaped electromagnet source :

As shown in Figure 3, an electromagnet (U-shaped) in principle could be designed to provide the necessary interacting magnetic flux. The calculations shown below are for a pole-face diameter of 1.5 m with an airgap of 4 m and a flux density across the gap of 5 gauss. The cross section of the yoke is chosen as 22 cm^2. Using the above values, the flux density B_m in the yoke works out to 4.545 kilo-gauss. Using 34% CO-Fe as the magnet material the corresponding magnetic field intensity H_m is 2.7 oersted. The resulting permeability value μ_r is 1683. The length of the yoke L_m is given by $L_m = \frac{\mu_r n B_g L_g}{B_m}$ where L_g is the length of the air gap.

Using the above numerical values the total weight of the magnet works out to 365 kgms. This compares favorably with the weight of the room temperature current loop configuration. The ampere turns (NI) required to drive the flux across the gap is given by (Nussbaum 1965) :

$$NI = \frac{B_m}{\mu_o}\left[\frac{(L_m - L_g)}{\mu_o} + L_g \frac{S_v}{S_p}\right]$$

where S_v is the area of cross section of the yoke, S_p is the area of the pole-face and μ_o is permeability of free space.

Using the above numerical values, $NI = 2535$ ampere-turns. Using AWG-8 wire and $I = 45$ amps and $N = 56$ turns, the power required $I^2R = 60$ watts. Other details of the design of the electromagnet are given in the reference (Kroon 1968) :

To summarize, for the U-shaped electromagnet :

Weight of the magnet : 365 kgms
Power required : 60 watts
Material : 34% Co-Fe
Gap flux : 5 gauss
Dimensions : as shown in Figure 3.

4. Results and discussion

Figure 4 shows the eddy current power input P_e and de-spin time T versus rpm for the current loop configuration. The specifications for the current loop are : $NI = 9000$ ampere-turns and radius, $A = 5$ meters. The satellite dimensions are : height, $h = 2.5$ meters, diameter, $D = 3$ meters, skin thickness, $T = 0.05$ meter. Figures 5 and 6 show the same parameters, namely, P_e and T versus rpm, respectively, for the case of the bar magnet and U-shaped electromagnet. The satellite dimensions are the same as indicated above. The magnet parameters are : (i) For the bar magnet : $M = 7.96 \times 10^5$ amperes/meter, radius $A = 0.087$ meter, length $D = 2.5$ meters and the center of the magnet is 1.85 meters from the cylinder surface ; (ii) For the U-shaped electromagnet : the gap flux is 5 gauss, diameter of the pole-face is 1.5 meter and the gap length is 4 meters.

The results shown in Figure 4 indicate that the de-spin time increases with increase in rpm after about 20 rpm for the case of the current-loop configuration. For both the magnet configurations as shown in Figures 5 and 6 the de-spin times increase with increase in rpm right from 1 rpm although for the case of the U-shaped magnet, the de-spin time seems to level off beyond 80 rpm. For the bar magnet configuration as shown in Figure 5, the de-spin time increases rapidly beyond 30 rpm. The reason for the increase in de-spin time is the result of the increase in the kinetic energy of the satellite as the square of the rpm and thus the kinetic energy increases much faster compared to the increase in P_s the eddy current power input to the satellite.

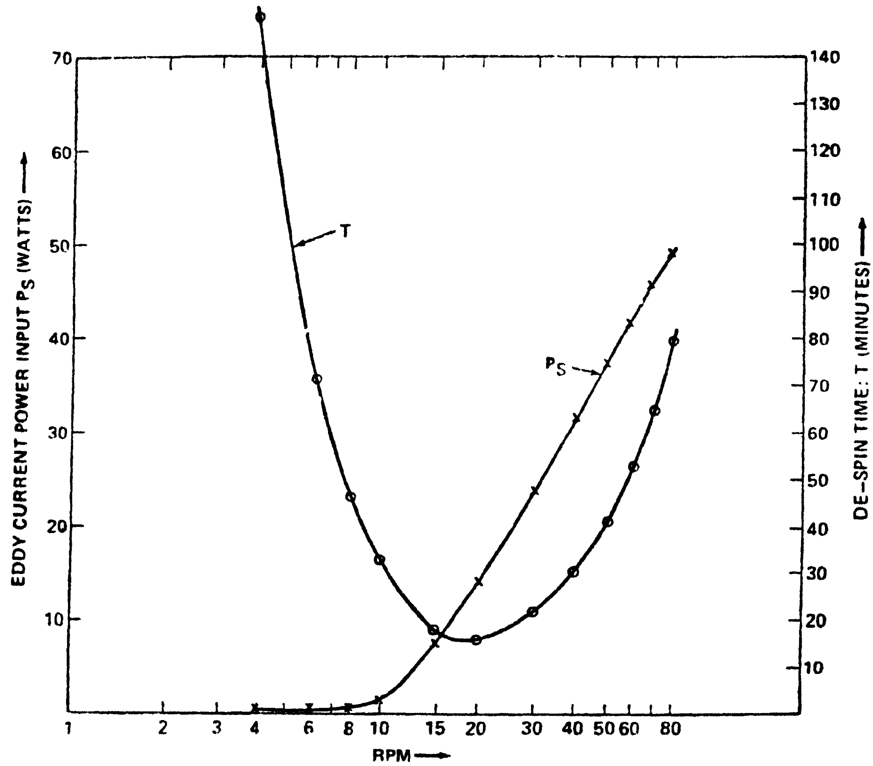

Figure 4. Eddy current power input, P_s, and de-spin time T, vs rpm for the current loop configuration. NI - 9000 ampere-turns. Loop diameter = 10 M, satellite dimensions : height = 2.5 M ; diameter = 3 M ; wall thickness = 5 cms.

The de-spin time at 80 rpm* for the bar magnet configuration is 156 minutes where as for the U-shaped magnet system it is 80 minutes. These results suggest that the bar magnet is less efficient for higher rpms compared to the U-shaped magnet. At rpms below 40, de-spin times are lower for the bar magnet compared to the U-shaped magnet. A comparison of the results in Figures 5 and 6 also indicate that the eddy-current power input P_s into the satellite is higher for the U-shaped magnet configuration compared to the bar magnet. This is to be expected as the U-shaped configuration with the pole faces encircling the satellite

*The possibility of satellites spinning as high as 80 rpm do exist as, for example, the application technology satellite ATS-6 referred to in the paper by Lenox (1984).

would be more efficient than the bar magnet in producing higher flux densities on the skin of the satellite.

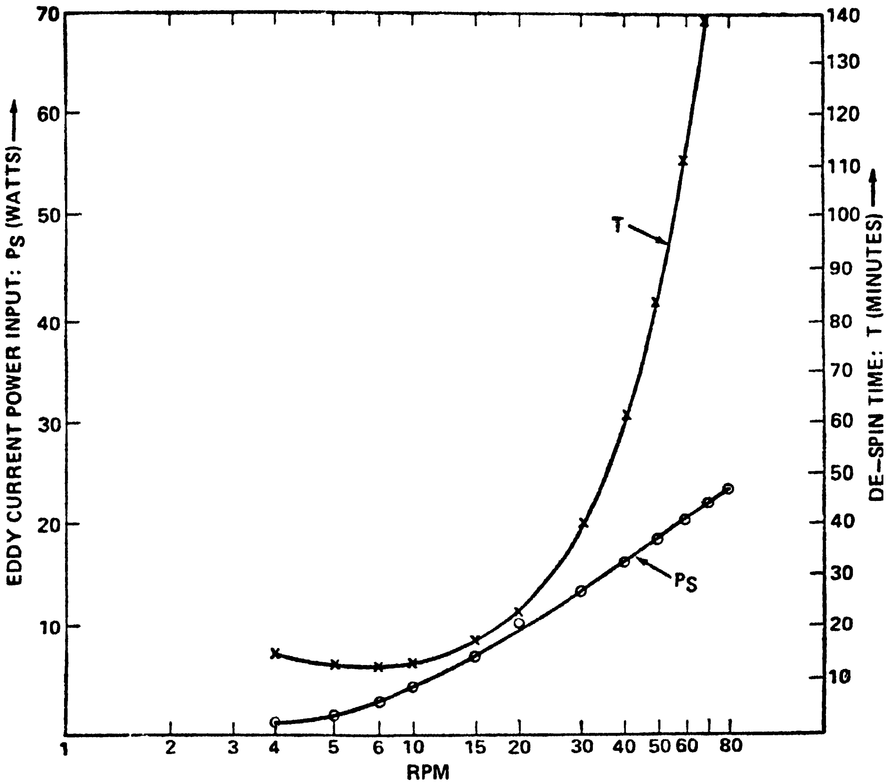

Figure 5. Eddy current power input P_s and de-spin time T vs rpm for the bar magnet configuration. Magnet dimensions : length = 2.5 M ; diam. = 0.087 M ; magnetization (M) = 7.96×10^5 A/M. Center of the magnet 1.85 meters from the cylindrical surface. Satellite dimensions : same as in figure 4.

Figure 7 is a comparison of the P_s values for the U-shaped magnet whose dimensions are given in Figure 3 and the 9000 ampere-turn current loop whose diameter is reduced to 8 meters. There seems to be good correlation between the two systems, the value at 80 rpm being almost the same.

It was thought interesting to see what effect the orientation of the bar magnet would have on the eddy current input. Results were obtained for orientation around the x-axis (Figure 2). It was found that P_s reaches a maximum around $X = 15^\circ$ and then drops off. For $X = 90^\circ$, P_s has the least value.

Table 1 below is a comparison of de-spin times for two satellites which differ only in skin thickness. The results indicate remarkably close correlation of the de-spin times from 1 to 10 rpm.

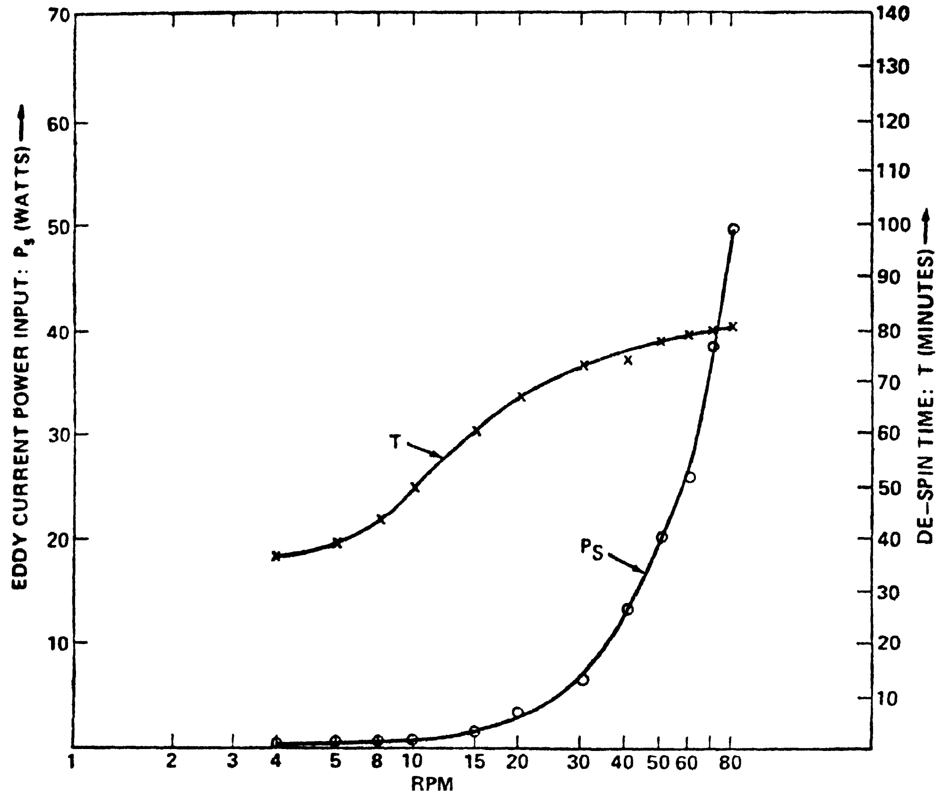

Figure 6. Eddy current power input P_s and de-spin time T vs rpm for the U-shaped electromagnetic configuration. Flux density in the air gap = 5 gauss ; diameter of the pole face = 1.5 M. Satellite dimensions : same as in figure 4.

5. Conclusions

The study undertaken in this paper, indicates that the non-contacting electromagnetic de-spin system based on the induction of counteracting eddy-currents into the skin of the satellite is practical and requires only moderate amounts of power. It would be possible to reduce satellite spin to a very low value within a reasonable time of the orders of orbital daylight or less.

A review of the weight considerations for the current loop and U-shaped magnet outlined in Section 3 suggests that both designs are equally preferred. Both yield reasonable values of de-spin times. Conceptually, perhaps, the coil configuration would be easier to implement than the magnet configuration. From the point of view of not using any external power, one could envision the use of a permanent magnet ; but the idea of carrying a large permanent magnet inside, for example, the shuttle may not be feasible in the practical sense. The air gap needs to be short-circuited while carrying the device into space ; but then the problem of

Table I. Comparison of the de-spin times in minutes versus rpm for the two satellites which differ only in the skin thickness. Magnet parameters : $M=7.96$ 10^5 A/M ; A 0.087 M ; $D=2.5$ M ; $D_{UB}=1.85$ M. satellite dimensions : $h=2.5$ M ; inside diameter $=2.9$ M ; skin thickness $-T$.

RPM	1	22	4	6	8	10
Satellite I ($T=0.05$)	2.0	2.85	6.4	13.5	26.2	49
Satellite II ($T=0.01$)	2.1	2.9	6.4	13.3	26.0	48

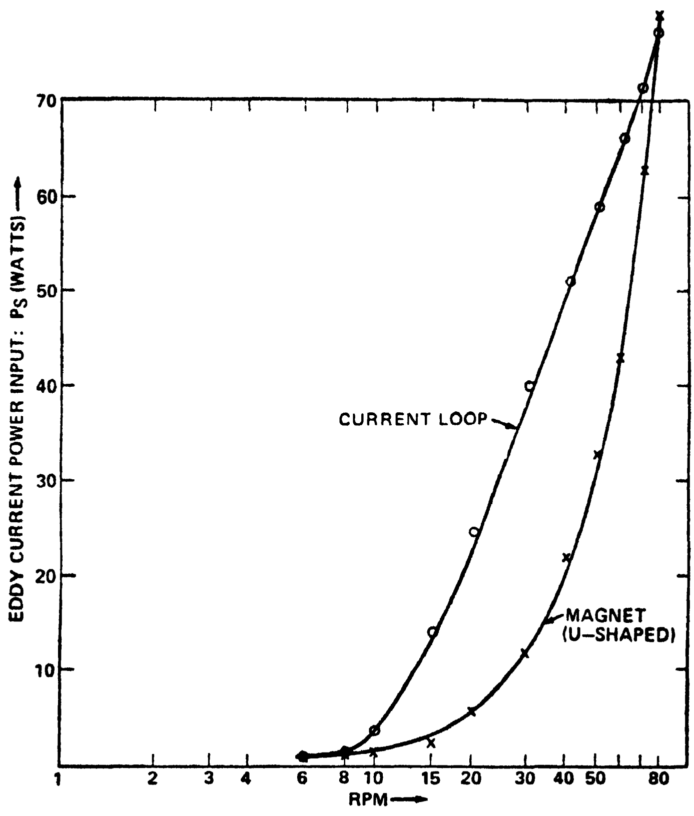

Figure 7. Eddy current power input vs rpm for current loop and U-shaped magnet : current loop : NI 9000 A-T ; diameter $=8$ M ; magnet : air gap $=4$ M ; diameter of pole face 2.5 M. Flux density across air gap -5 gauss. Satellite dimensions : height $=2.5$ M ; diameter $=3$ M. Wall thickness 5 cms.

removing the 'keeper' and creating the large air gap is not realizable in the practical sense as suggest by (Kusterbuck 1984).

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